


ASTERIA being deployed  
from the NanoRacks CubeSat  
Deployer on the International  
Space Station



Mars as viewed by MarCO-B  
after the InSight entry,  
descent, and landing

# Adaptations of Guidance, Navigation, and Control Verification and Validation Philosophies for Small Spacecraft

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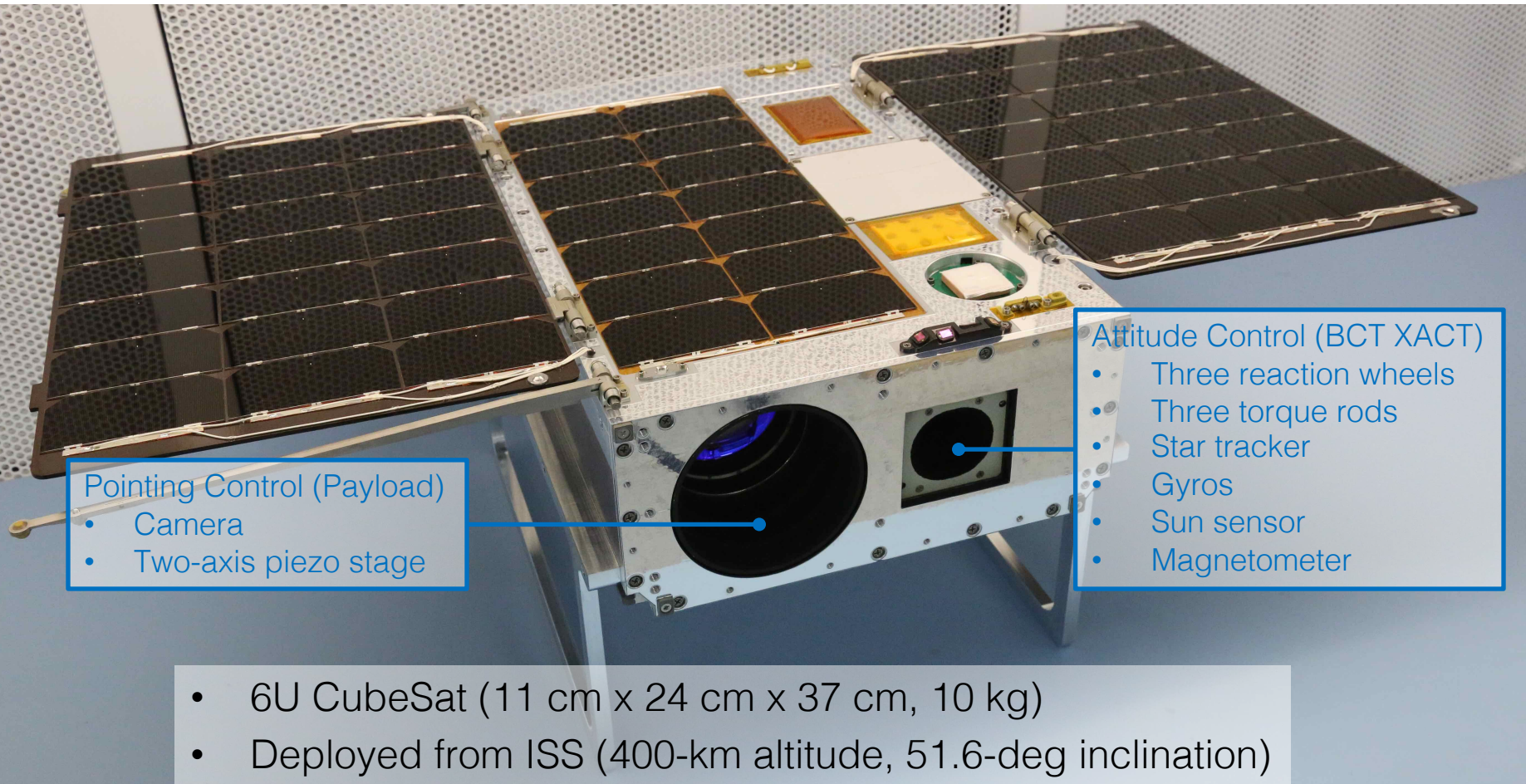
# Overview

- JPL CubeSat conundrum: Tug of war between limited schedule/budget and delivering a product with high probability of success
- Comparison of two successful JPL CubeSat missions (ASTERIA and MarCO) versus a flagship mission (Mars 2020)
  - ASTERIA/MarCO budget: On the order of \$10 million
  - M2020 budget: \$2.1 billion
- Cover various aspects of guidance, navigation, and control (GN&C) verification & validation (V&V):
  - Requirements definition
  - Software testing & analysis
  - Hardware component testing
  - Integrated vehicle testing
  - In-flight verification and validation

Retrospective analysis of GN&C V&V performed on ASTERIA & MarCO versus M2020 to help guide future small spacecraft missions

# ASTERIA Overview

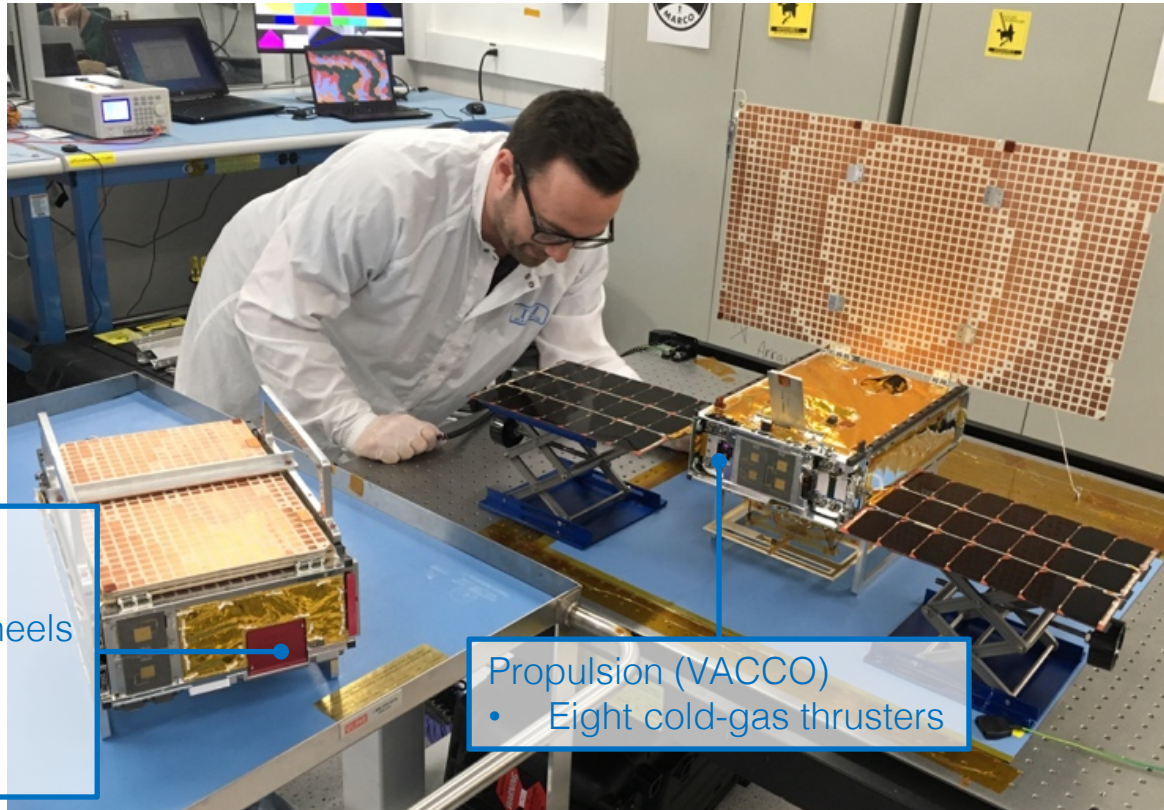
## Arcsecond Space Telescope Enabling Research in Astrophysics



Perform photometry on bright stars, which requires repeatable and stable pointing



# Mars Cube One (MarCO) Overview



## Attitude Control (BCT XACT)

- Three reaction wheels
- Star tracker
- Gyros
- Two sun sensors

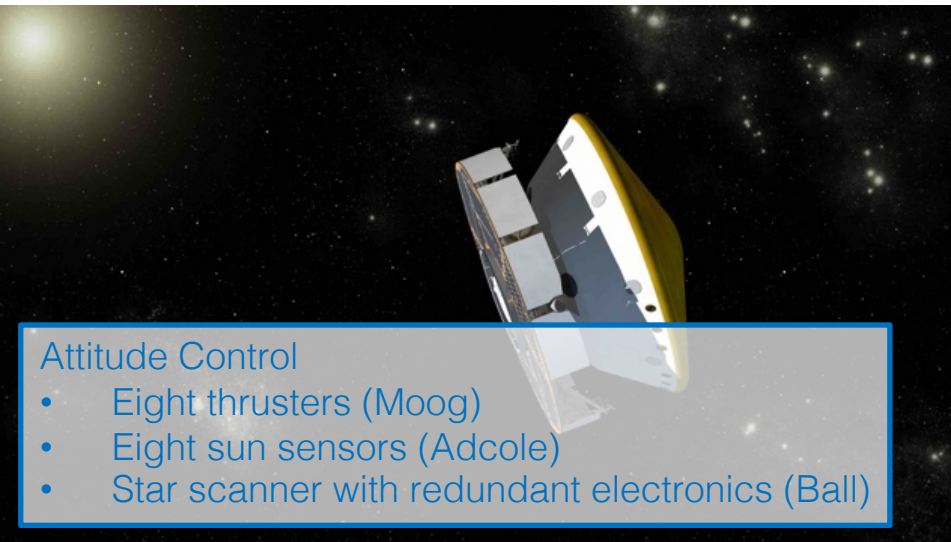
## Propulsion (VACCO)

- Eight cold-gas thrusters

- Two 6U CubeSats (11 cm x 24 cm x 37 cm, 14 kg)
- JPL Iris X-band transponder

Perform bent-pipe relay of InSight's entry, descent, and landing at Mars.  
Three-axis attitude control for power and communication.  
Propulsion for momentum dumping and trajectory control maneuvers.

# Mars 2020 (M2020) Overview



## Attitude Control

- Eight thrusters (Moog)
- Eight sun sensors (Adcole)
- Star scanner with redundant electronics (Ball)



- JPL's next Mars rover, carrying seven science instruments
  - Characterize the geology around the landing site
  - Seek preserved biosignatures of microbial life in rock samples
  - Collect and cache rock and regolith samples
  - Prepare for humans, including the in-situ production of oxygen
- Launching in July/August 2020 for landing in February 2021

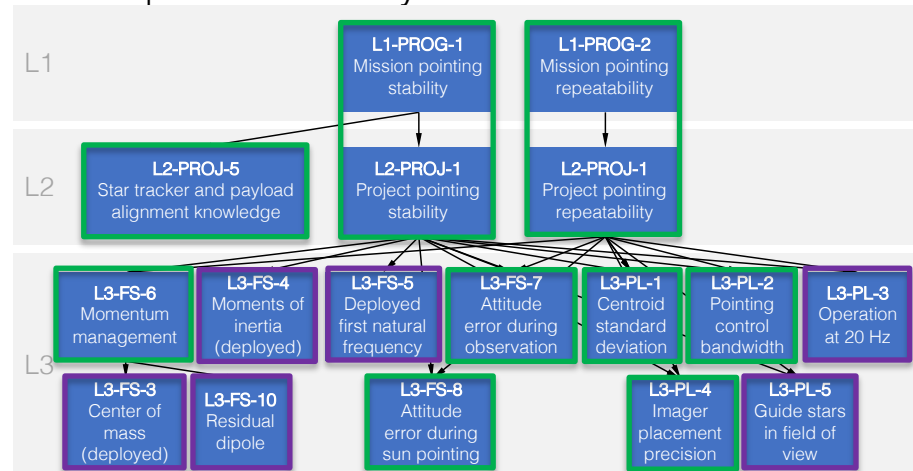
Flagship mission, focusing on cruise attitude control as an appropriate analog. Spin-stabilized attitude control and ability to perform trajectory control maneuvers.

# Requirements Flow-Down

- Traditionally a rigid, formal flow-down process
  - L1 program, L2 project, L3 flight system, L4 subsystem, and L5 component requirements
- ASTERIA/MarCO performed an as-needed flow-down, resulting in fewer requirements (and fewer levels)
  - Subcontracted entire attitude control subsystem. Less of a need to flow requirements down to component level.
  - Smaller team. More important to flow requirements for system-level interactions than down into a subsystem.

Example of ASTERIA requirements flow-down:

- 9 GN&C requirements
- 6 GN&C-related requirements levied on other subsystems

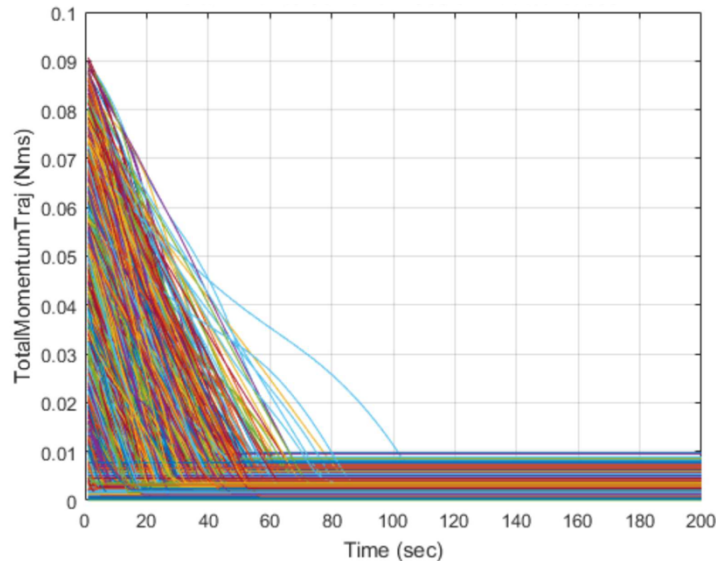


- M2020 has 31 L4 GN&C, 51 L5 cruise ACS, 17 L5 digital sun sensor, and 13 L5 star scanner assembly requirements (112 total requirements)

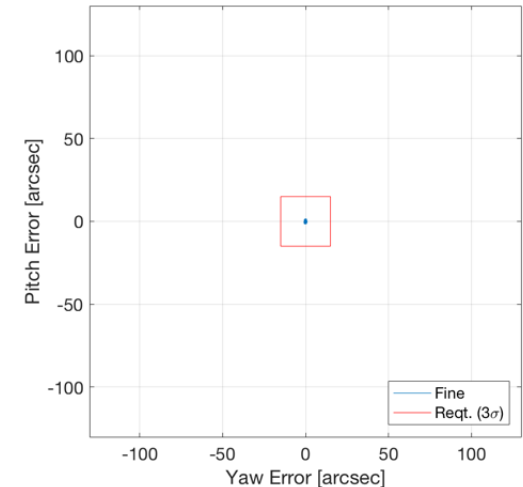
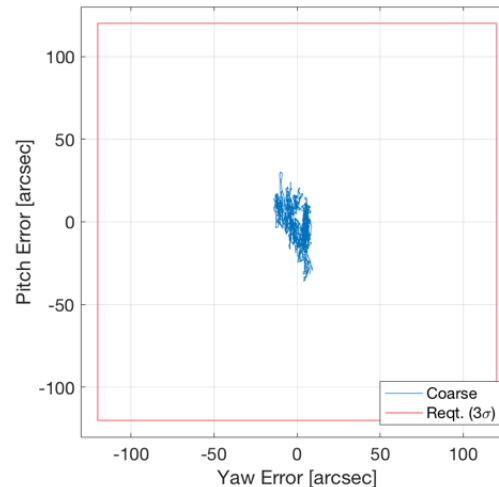
Paring down the requirements means less process overhead and more design flexibility, but comes with increased risk

# GNC Software Testing and Analysis

MarCO Momentum Dumping Monte Carlo Simulation



ASTERIA Simulated Attitude/Pointing Errors



- MarCO subcontracted out attitude control simulation and analysis to BCT
- ASTERIA has a time-domain simulation and frequency-domain analysis for testing flight software and creating error budgets (in addition to BCT's standard XACT analyses). Leveraged past work to cut down on costs.
- M2020 has a time-domain simulation and an error budget analysis

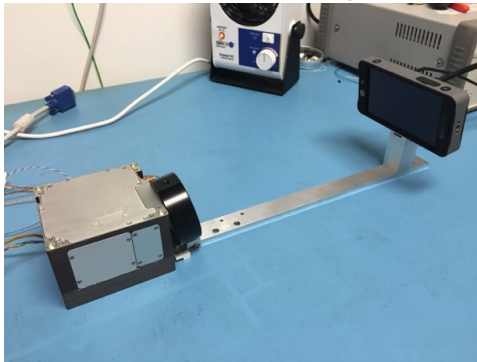
Regardless of spacecraft size, it is necessary to perform sufficient software testing and analysis to ensure requirements are met.



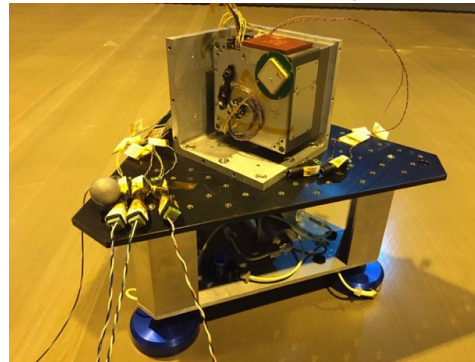
# GNC Hardware Component Testing

- ASTERIA/MarCO did not have L5 requirements to verify during hardware component testing. Focused on functional/performance tests, which were considered verification items.
- **Modifications** of typical hardware-component-level tests performed on M2020
  - Ensuring the hardware turns on and can be commanded
  - Produces desired actuation or measurements within tolerance
    - Characterized performance instead of verifying requirements
  - Stays within required power constraints
    - Characterized power usage to update power budgets, instead of verifying requirements
  - Survives and/or operates in the specified pressure, temperature, vibration, electromagnetic, and radiation environments
    - Deferred thermal-vacuum, vibration, and electromagnetic testing to system level unless performed by vendor
    - Leveraged radiation testing of a similar XACT unit. Did not perform radiation testing of piezo stage and electronics
  - Added: Phasing of XACT at a "component" level

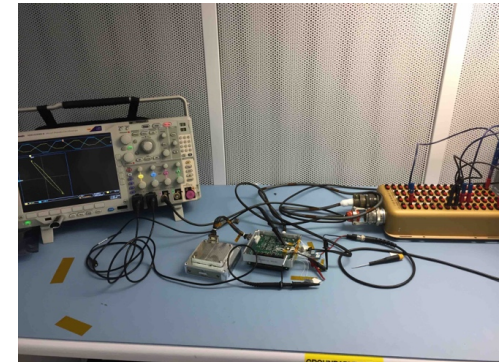
Star Tracker  
Functional/Phasing Test



Reaction Wheel  
Functional/Phasing Test



Piezo Stage  
Functional/Performance Test



Hardware component tests focused on phasing  
and functionality assessments rather than requirement verification

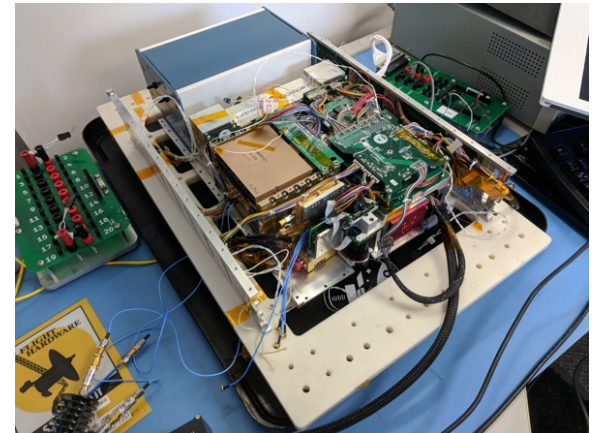


# Integrated Vehicle Testing

M2020 Venues	Hardware	Software	Simulation Type	Availability	Testing
Work Station Test Set (WSTS)	None	Complete flight software	Software-in-the-loop	Can be scaled to usage	Software V&V MSTB/ATLO procedure development
Mission System Testbed (MSTB)	Engineering models		Hardware-in-the-loop	Limited	Software V&V <del>ATLO procedure dry runs</del> Flight ops dry runs
Assembly, Test, Launch Operations (ATLO)	Flight hardware			Very limited	Hardware/software V&V Mission scenario tests

- ASTERIA/MarCO did not have a WSTS venue due to lack of time/resources and inevitable idiosyncrasies, but at the cost of increased demand on testbed/flight system
- Both had a testbed for including an ACS hardware-in-the-loop simulations. Invaluable for testing after flight system delivery.
- Less of an emphasis on procedure writing/polishing. More of an emphasis on time spent testing, finding/fixing bugs.

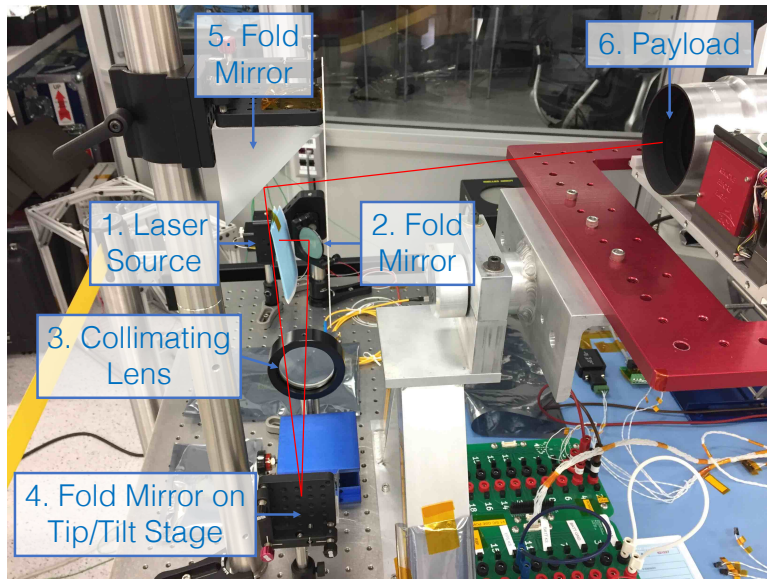
MarCO Testbed



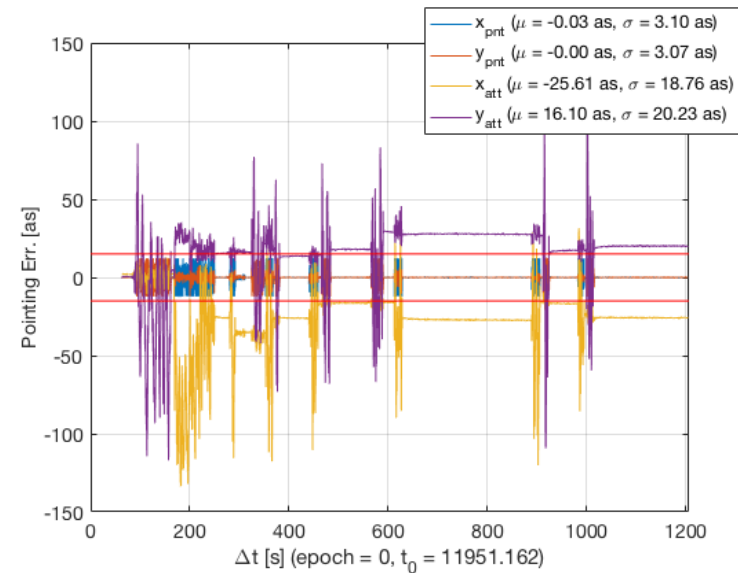
Decoupling of WSTS venue and procedure development allowed for increased time spent testing, increasing reliability, while staying within project time/cost constraints

# Integrated Vehicle Testing (ASTERIA Example)

ASTERIA Closed-Loop Payload Test Setup



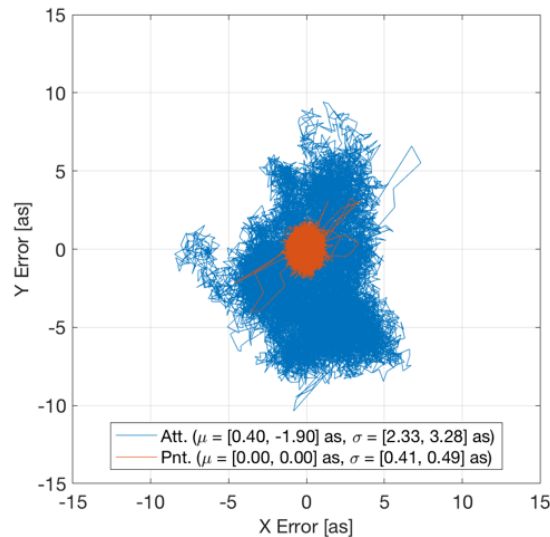
Attitude/Pointing Error in Closed-Loop Functional Test



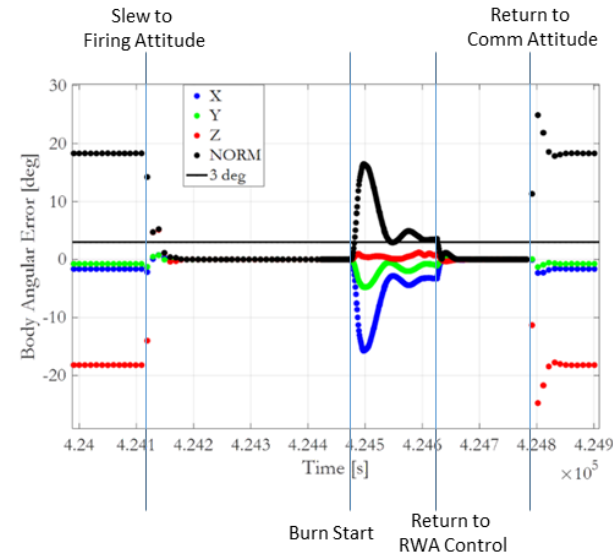
- ASTERIA/MarCO did not use 3-DOF air bearing platform testing due to time/resource constraints, implementation hurdles, and inability to use them for performance characterization
- ASTERIA performed a simple, closed-loop test at the system level to demonstrate end-to-end functionality of the pointing control system
  - Moved external tip/tilt mirror to simulate “attitude” errors and have the pointing control system react
  - This combined with performance tests in simulation were sufficient to V&V ASTERIA L2 pointing requirements prior to delivery

# In-Flight Verification and Validation

Attitude & Pointing Error  
Scatter Plot for HD 219134  
Observation on ASTERIA



Angular Error from Commanded  
TCM Attitude of MarCO-B TCM1  
Segment on 2018 Day of Year 141



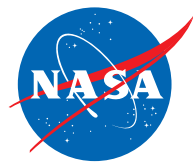
- Technology demonstration missions have L1 requirements that cannot be verified until in flight
  - ASTERIA: L1 pointing stability (5 arcseconds RMS over 20 minutes) and repeatability (1 arcsecond RMS from observation to observation)
  - MarCO: Perform up to five trajectory correction maneuvers to enable a Mars flyby to support InSight's entry, descent, and landing communications as a bent-pipe relay platform

Successful achievement of GN&C requirements in flight are a testament to the V&V process used despite tight cost/schedule constraints

# Conclusions

- Items that can be scaled down to fit within tight schedule and cost constraints:
  - Flow-down of requirements
  - Number of simulation environments
  - Complex integrated-system-level tests
  - Procedure development and use (but not documentation of tests)
- Items that should not be scaled down:
  - Testing of essential GN&C verification items
    - Performance
    - Functionality
    - Phasing
    - Timing
  - Ability to defer development and testing
    - Ability to update flight software in flight
    - Testing of essential commands and telemetry channels pre-flight
    - Ability to use ground testbeds throughout the full mission lifecycle
    - Ability to send arbitrary commands to vendor-provided hardware





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